Overview of the Space Toilet History

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One of the most critical parameters of life support for receiving, storing, and disposing of human waste has been provided throughout the history of manned spaceflight by the development and application of a wide variety of toilet systems, ranging from disposable equipment in short-term spaceflights to complex systems with waste pre-treatment as part of the regeneration complex of orbital stations. The history of space toilet development and application from 1961 to the present is part of the history of life support system development, including the vast experience of successful solutions, elimination of errors and shortcomings, and development along with improvements in space technology. Knowledge of this history is useful to design engineers, operations engineers, and astronauts, and is critical to the successful design of toilet systems for new space missions.

Acronyms and Nomenclature

*Note: *-acronyms are English translations of the original Cyrillic acronyms*

ASU*	=	sewage and sanitation device	SSHO*	=	sanitary and hygienic support facilities
ASU SPK-U*	=	urine feed, separation and pretreatment system with sanitation device	TPVF*	=	porous foamed polyvinyl formal
			UCD	=	urine collection device
ISS	=	International Space Station	UCTA	=	urine collection and transfer assembly
KTO*	=	solid waste (fecal) container	UPA	=	urine processor assembly
LSS	=	life support systems	URA	=	urine receptacle assembly
MLM	=	multi-purpose lab module	USOS	=	US orbital segment of the ISS
RS ISS	=	Russian segment of the ISS	UTS	=	urine transfer system
SM	=	Service Module	UWMS	=	universal waste management system
SOT*	=	wring collector (back-up static separator)	WHC	=	Waste and Hygiene Compartment
SRV-U*	=	urine reclamation system of RS ISS	WRS	=	water recovery system

I. Introduction

Human excretion of urine and feces is about 650 kg/person (1430 lb/person) per year and is the second by mass factor in the mass balance of the human body after water consumption, and the second by critical residual time for human life after carbon dioxide, depending on the volume of the closed habitat. At the same time, zero gravity in space flight has the greatest impact on technical possibilities of human urine intake along with water use for personal hygiene, compared to, for example, water and food consumption, and even more so to providing an atmosphere for breathing.

In other words, it is simply impossible to go to the toilet without special technical means in the conditions of space flight. The importance of the toilet in the habitat complex is undeniable, although it has not always been fully considered by space mission designers, especially in the early stages of projects, as weight and volume limitations and funding constraints have periodically relegated toilets to a secondary role compared to, for example, water and gas systems.

The design of devices to collect urine and feces from spaceflight crews began concurrently with the development of the first life support systems, and even the first space testers - dogs - were provided with urine and feces collection containers. The main challenges in the early stages were how to accept human urine and feces in microgravity and

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how to provide for their temporary storage and disposal in the confined environment of the spacecraft. The comfort of the human need to go to the bathroom was not a priority in the design of life support systems in the early stages of manned flight. There were no toilets as such on the first American spacecraft. Instead, they used disposable means in the form of bags and urinals designed for a short flight. On Soviet manned spacecraft, starting with the first Vostok spacecraft, technical means were installed, including electric air pumps, which in microgravity conditions ensured the collection and transport of urine from a person to a storage tank. This equipment became the basis for real space toilets.

The design of toilets evolved with the rest of the life support system as the duration of crewed space missions, the number of crew members, and the volume and confinement of the habitat increased. The space toilet first became a separate technical device using transport air to receive urine and feces on the Soyuz spacecraft and Skylab orbital station. Then it became a system with separation of liquid urine from air, reusable urine collection tanks and feces containers on the Skylab and Salyut orbital stations, and finally a part of the regeneration life support complex with urine pre-treatment and provision of water regeneration from it on the MIR and ISS stations.

A separate milestone in the history of space toilets is undoubtedly the international project of the NASA Waste and Hygiene Compartment (WHC) with Russian toilet ASU, made to complete the regenerative life support complex on the American segment of the ISS.

In the process of development, space toilets have become more comfortable and reliable, designed for long-term operation under conditions of permanent human stay on the space station. Urine pre-treatment technologies provide not only regeneration of water from urine, but also significantly increase the safe storage time of urine when it is disposed of and the resource of air purification filters, significantly reducing odors from the toilet. The history of improving space toilets, lessons learned from their operation and original technical solutions are the basis for their further development and design of new toilets for manned missions to the Moon and Mars.

II. Urine and fecal collection on the first US manned spacecraft

The first two U.S. manned spacecraft, Mercury-3 and 4, did not include any means of urine and feces intake. They were suborbital flights of 15 minutes (Mercury-3, Alan Shepard, May 05, 1961) and 16 minutes (Mercury-4, Virgil I. Grissom, July 21, 1961). The first urine collection device (UCD) was introduced on Mercury-6 during the first orbital flight (John Glenn, February 20, 1962, 4 h 55 min) and consisted of a tube with a rubber cuff and a container for urine collection (Figure1).[1]

Figure 1. Mercury UCD

The first UCDs could not be used for female astronauts, whose flights were not yet planned. For the last Mercury flight - Mercury-9 (Leroy Gordon Cooper, May 15, 1963, 1 day 10 h 20 min), the UCD was supplemented by a system for urine drainage and temporary storage: an on-board tank connected to the UCD by a hose with a hand pump. The collection of feces on the Mercury spacecraft was not foreseen at all; the astronauts were on a special diet before the flight to avoid the excretion of feces.

UCDs were not sufficient for long-duration flights in the two-seat Gemini spacecraft, and new long-duration aids were developed for use in orbit. UCDs continued to be used at launch with diapers (optional) on later Gemini, Apollo, and Space Shuttle missions.

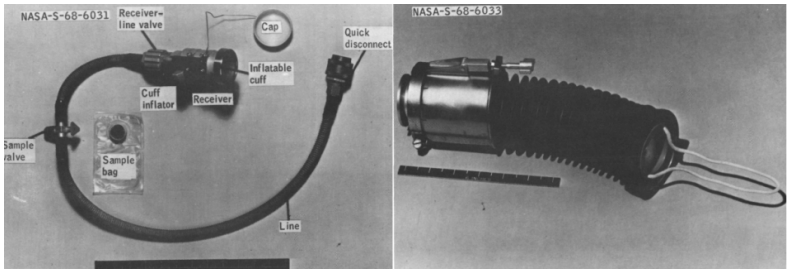


Figure 2. Gemini first Urine Receptacle

The original orbital design for Gemini-3 (March 23, 1965, 4 h 53 min) and Gemini-4 (June 3, 1965, 4 days 1 h 56 min) called for the use of a urinal with simultaneous thrust generation by a hand pump "accordion" receiver (Figure 2).

This design had serious drawbacks: first, the use of a hand pump required the assistance of a second astronaut, and second, due to flaws in the "accordion" design, the system often ejected urine instead of transferring it. Beginning

with Gemini 5 (August 21, 1965, 7 days 22 h 55 min), the system was modified - the urinal was made to fit tightly, like a condom, a non-return valve was added to the tube to prevent urine ejection, and the receptacle was replaced by a simple soft container (Figure 3).[2]

Starting with Gemini, urine (except for small bags for later medical analysis) was not stored on board but discharged through a special heated valve. According to astronauts, one of the most beautiful spectacles in space was the urine discharge at sunset (astronaut Russell Louis Schweickart). The urine turned to ice and dispersed beautifully in an icy cloud.

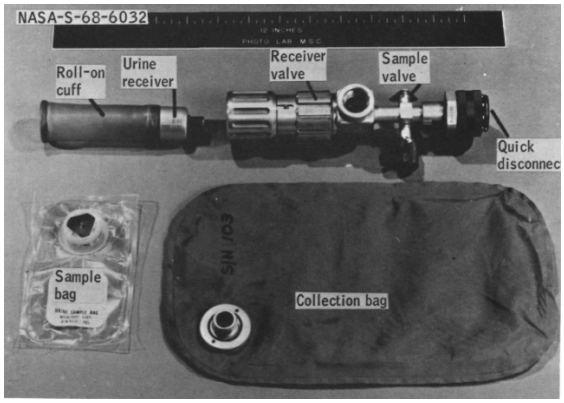


Figure 3. Gemini Urine Receptacle

The extended flights of the Gemini Program led to the requirement for a defecation system. Special bags were developed to collect feces (Figure 4). The bag had an adhesive neck and had to be taped to the buttocks around the anus. After defecation, it was necessary to insert one's fingers into the special finger cot, separate the feces from the body, and push them further into the bag so that they would remain contained. Then it was necessary to tear open the germicidal agent bag, put it into the large bag with feces and mix it - this was necessary to kill bacteria and prevent gassing in the bag. Then came the toilet paper and wet wipes, and finally it was time to put it all in another bag and put it in the trash.

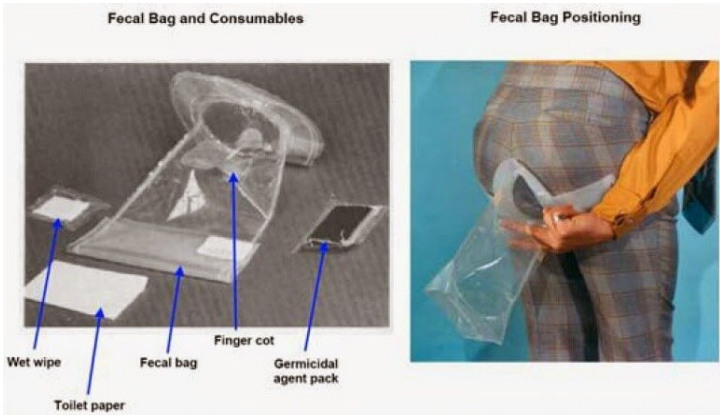


Figure 4. Gemini/Apollo fecal bag

By the astronauts' own admission, it was not the most comfortable way to dispose of feces - the glue on the neck of the bag pulled on skin and hairs, it took about 45 minutes to go to the toilet, and there was no way to avoid filling the cabin with unpleasant odors. Because this task was distasteful and took an inordinate amount of time, low-residue foods and laxatives were generally used before launch. During flight, in addition to low-residue foods, some use was made of drugs to reduce intestinal motility.

For the Apollo missions, the fecal bags were used during in-vehicle activities. During lunar surface activity and free space extravehicular activity, the use of the bag fecal collection system was not feasible. Should it have become impossible for a crewman to have prevented defecation during these activity periods, the fecal containment system - a pair of undershorts with layers of absorbent material - would serve to contain any excreta.

The urine collection and transfer processes, with only minor modifications, were essentially the same for Apollo missions as they were for all prior United States space missions. Very simply described, the prime system used prior to Apollo 12 (November 14, 1969, 10 days 4 h 36 min, second lunar landing) by unsuited crewmen employed the Urine Transfer System (UTS). This system consisted of a rubber cuff connected to a flexible collection bag. The urine receptacle

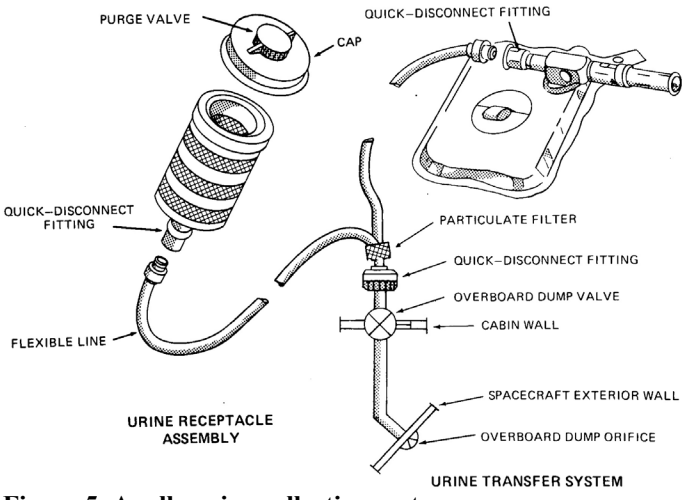


Figure 5. Apollo urine collection systems

assembly (URA) was developed for Apollo and served as the prime system on Apollo 12 and a subsequent mission (Figure 5). This system employed a device which did not require intimate contact of the crewman during urine collection.

When crewmen wore space suits during launch, extravehicular activity, and emergency modes, a special device was provided for collection and intermediate storage of urine (Figure 6). The assembly was connected by a hose to the spacecraft waste management system. Several modified devices were used when urine samples were collected for postflight analysis.

Figure 6. Apollo Urine Collection and Transfer Assembly

The Apollo waste management system (WMS) controlled the disposition of solid and liquid wastes and waste stowage gases. The basic requirements of the system included collection and stowage of feces, collection and overboard dumping of urine, removal of urine from the pressure garment assembly, provision for urination while in the spacecraft couches, and venting of waste stowage gases. A urine and fecal waste stowage vent and a vacuum subsystem were part of the overall waste management system. The waste management system consisted of a urine subsystem and a fecal subsystem. The principal elements of the urine subsystem were the URA, the UTS, the urine collection and transfer assembly (UCTA), and, for several missions, modified urine collection devices to provide samples to be retained for postflight analysis. The main elements of the fecal subsystem were a fecal and emesis collection device, a waste stowage compartment, a waste stowage bag, and a fecal containment garment for contingency and suited conditions. Figure 7 is a schematic representation of the waste management elements within the Command Module (URA not shown). The system design included a particulate filter to prevent clogging of the orifice of the urine dump nozzle (see Figure 5) and a hose for transferring urine from any of the collection devices to the waste management panel for dumping. The URA was an open-ended, cylindrical container that could be hand-held. The receptacle was connected by a quick-disconnect fitting to a flexible urine dump line, which in turn was connected by a quick-disconnect fitting to the waste management panel. The receptacle could accommodate maximum urine flow of 40 ml per second. Although the receptacle's volumetric capacity was only 480 ml, the effective system capacity was 700 ml with concurrent urination and dumping. The URA contained a honeycomb cell insert that supported a 40/a hydrophilic screen. The honeycomb insert provided a large contact area that acted as a bundle of capillary tubes. The capillary action produced by each cell (0.32 cm pore size) of the honeycomb tended to hold the fluid in place in the zero-g environment until it could pass into the urine dump line. A sealing cap installed during periods of nonuse blocked out cabin airflow and permitted the interior of the URA to be exposed to the space vacuum for venting between uses, if desired.[3]

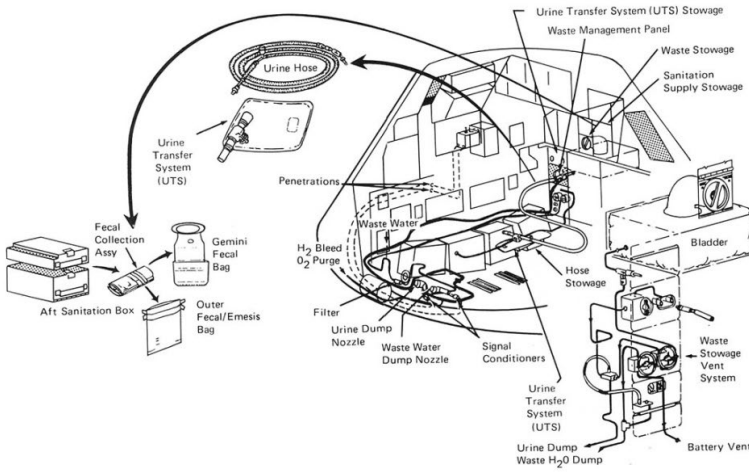


Figure 7. Apollo Waste Management System diagram

III. Urine and fecal collection on the first Soviet manned spacecraft

The first Soviet Vostok spacecraft was equipped with a toilet, Sewage and sanitation device (ASU) from the very beginning. The first cosmonaut Yuri Gagarin did not use the toilet for his 1 hour 48 min orbital flight on April 12, 1961. The second cosmonaut of the USSR German Titov was the first to test the space toilet for urine collection during his daily flight on August 6, 1961 (25 hours 18 min), and Valery Bykovsky was the first to use it for feces collection during his flight on Vostok-5 (June 14, 1963, 4 days 23 hours 6 min).

Considering that the whole first space flight was to be spent in a spacesuit without leaving the ejection seat, the work on the creation of a sanitary device for the Vostok spacecraft was carried out in parallel with the work on the spacesuit and the seat. It should be emphasized that at that time there was no practice of creating such devices for the

conditions of absence of gravitational forces (and after all, it is the gravitational forces in everyday life that provide relative simplicity of solving the problem of collecting body wastes).

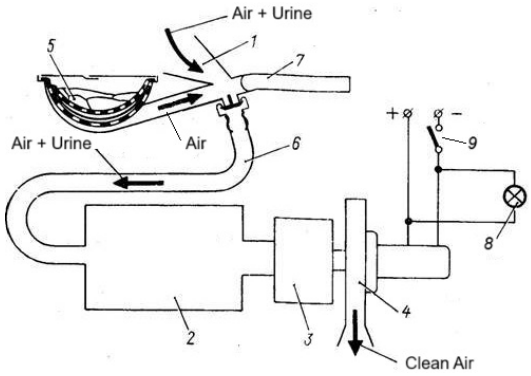


Figure 8. Vostok ASU diagram
1 - receptacle; 2 - moisture collector; 3 - air filter; 4 - fan; 5 - fecal liner (bag); 6 - flexible hose; 7 - handle; 8 - signal lamp; 9 - toggle switch.

Figure 9: Vostok ASU receptacles
1 - male; 2 - female;

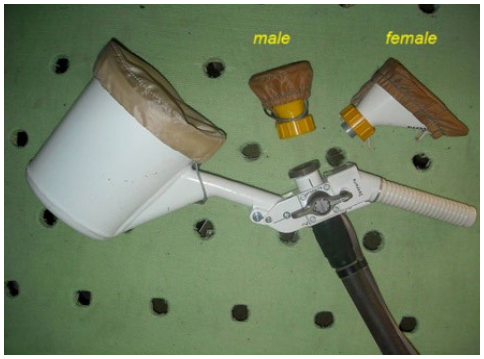


Figure 10. Soyuz vehicle Receptacle with exchangeable funnels, male and female

The key issue of device operation in microgravity was solved by incorporating a fan into the device (along with the vessel-receptacle, moisture collector, air purifying filter, and feces collector). The fan provided a constant flow of air through all the other elements during operation of the system. This air flow enabled the liquid waste to be transported from the point of collection to the point of isolation and storage, i.e. from the receptacle to the collection tank, and also provided the collection and retention of solid waste in the feces collection tank during use (Figure 8).

The unique environment in which the device had to operate affected almost every element. For example, the receptacle - which included a funnel to receive liquid waste and a cup with disposable liners to receive solid waste - had an elongated handle that allowed the receptacle to be inserted into the spacesuit through a special attachment in the spacesuit shell. The shape and dimensions of the receptacle were chosen taking into account the conditions for combining it with the spacesuit (Figure 9). The great advantage of the toilet was its suitability for both men and women, provided by interchangeable urine and feces receptacles. For a flight with a female cosmonaut, a female receptacle was installed in the ship, which could easily be replaced by a male one. This approach is still used on Russian Soyuz spacecraft, where an additional female or male receptor is stowed in the ship's orbital module container and its replacement is provided for during flight (Figure 10). The first flight of a woman in space took place on June 16, 1963 - Vostok-6, Valentina Tereshkova, 2 days 22 h 50 min.

Liquid waste entering the receiver funnel, together with the conveying air, formed a gas-liquid mixture under microgravity conditions, which was conveyed to the moisture collector via a hose. The moisture collector was a static gas-liquid separator operating based on capillary forces. Liquid waste in the moisture collector was absorbed by a moisture-absorbing material, porous foamed polyvinyl formal (TPVF). Its finely cut cubes filled the entire internal cavity of the moisture collector. Labyrinth channels formed between the TPVF cubes ensured both sufficiently low hydraulic resistance of the moisture collector and complete absorption of liquid from the gas-liquid mixture. A deodorizing filter was placed at the outlet of the moisture collector to ensure purification of the air stream from harmful and unpleasant gaseous impurities. The purified air was discharged into the cabin atmosphere by a fan.

The device used on Vostok series ships was designated "ASU-III" and was designed as a single unit with a receiver attached to it on a flexible hose. In the future, variants of systems ASU-V, ASU-VI were created and used. Designed for a longer period of use, they were constructed on the same principles as ASU-III (a single unit inscribed in a given space with a moisture collector-separator).

For **Voskhod-1** (launched on October 12, 1964) and **Voskhod-2** (launched on March 18, 1965) a new type of ASU system called "Fialka" (Violet) was developed. In this system, in contrast to "ASU-III", the functions of a single collector-separator were assigned to separate units. The gas-liquid mixture from the collecting unit fell into the separator, in a helical channel of which the phase separation took place, while the liquid was absorbed by the moisture-

absorbing material of the peripheral walls of the channel. At the same time, a special pump, which constantly created a working vacuum, pumped the liquid out of the moisture-absorbing material of the separator through nickel-metal-ceramic elements. After a signal indicated that the pump was full, the contents were squeezed by pressing the pump handle. The squeezed liquid was directed through a hose to storage collectors. Rubber bags placed in metal housings served as collectors. The air from the separator was sent through “Block-II”, which consisted of a deodorizing filter and a fan. The use of such systems promised great advantages in terms of volume savings in the storage of liquid waste. Fialka-III was used in the **Soyuz-1 - Soyuz-8** missions (April 23, 1967 - October 13, 1969).

During the design of the Soviet Moon Program in 1964-1969, the Fialka-IV system was designed for the L-1 (lunar orbit) variant. It differed from the "Fialka-III" system in the increased capacity of the separator and the pump, as well as in the fact that the liquid collectors were mainly the tanks of the "Kolos" water supply system, which were gradually emptied of drinking water during the flight.

For the L-3 variant (landing on the Moon), the variant called ASU-VII proved to be preferable from the point of view of minimizing the mass during return from the lunar orbit. This system consisted of several units connected by hoses, including: a traditional receiving device, three interchangeable moisture collectors-separators (collectors) and a unit containing a deodorizing filter with a fan. The collectors had an optimal cylindrical shape, designed so the volume of the one collector would be sufficient for the period of return of the crew of two people from the Moon to the Earth. This made it possible to exclude the mass of the other two collectors and the liquid collected in them from the mass on the back flight from the Moon to Earth, by dropping it, for example, into lunar orbit from the main spacecraft and then dropping them onto the lunar surface. The first two collectors were to be used sequentially in the initial phase of the flight (with a sufficient capacity reserve). At the same time the possibility of visual control of overfilling of the collector was provided with the help of a "slip indicator" - a dripping liquid sensor installed on the collector outlet fitting which at this stage was not only visual but not electrical.

Figure 11. ACY-VII emergency receptacle with wringer

For the ASU-VII system, an emergency device called a "receptacle with wringer" was developed to ensure urine collection without turning on the fan, although prototypes of such a device were included in earlier systems. The device is a tube with a rubber cuff connected to a urine reservoir by a hand pump, a rubber "pear" with two check valves at the inlet and outlet (Figure 11). When using the device, the astronaut squeezed the "pear", which squeezed the urine out of the container through a check valve, and then released it, and the rubber pear sucked the urine through a tube hermetically connected to the body. Such a device could only be used by men, but it was part of the emergency kit until 2008, when a second toilet was added aboard the ISS, and it came to the rescue in dire situations.

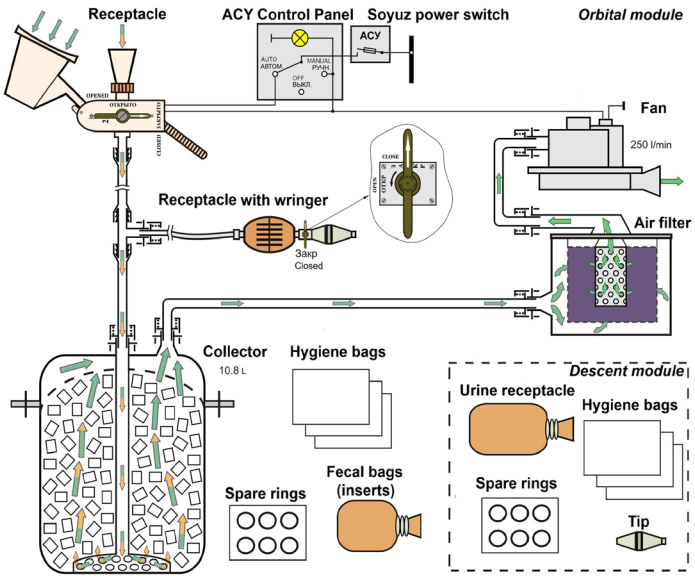


Figure 12. ASU-VIID of Soyuz-MS vehicle

When the Soyuz-9 spacecraft (launched on June 1, 1970) had to provide a crew flight of more than 17 days, it became clear that the Fialka-type devices were not suitable for such a task because the separators of these products had a lower lifetime than required. It was determined that salts precipitated from urine over time clogged the pores of the nickel metal ceramic elements, causing the separator to fail. Since the development of the ASU-VII system was fully completed by this time, it was decided to use a modification of this system, designated "ASU-VIIA", to support the Soyuz-9 flight. The ASU-VIIA system consisted of two self-contained units. One part consisted of a receiver, a cylindrical moisture collector-separator

(collector from the "ASU-VII" kit) and a "filter-fan" unit. In order to save the collector's life, this part was usually used only for simultaneous collection of urine and feces. If only urine was collected, another set was used, consisting of individual "squeezers" and a collection unit in the form of a rubber bag placed in an open metal container and equipped with a protective fabric cover.

The tanks of the water supply system, emptied sequentially of drinking water, were also used as collectors, which allowed a significant saving of volume occupied by the ASU system.

Based on the results of the Soyuz-9 flight, the calculated useful volume of the moisture collector-separator was confirmed, and it was concluded that the use of a receptacle with wringer is expedient only as an emergency tool.

After the Soyuz-9 spacecraft, the main task of the Soyuz spacecraft was to perform transport operations for work with long-term stations, which is associated with a long interruption of the operation of the transport space vehicle's ASU while the crew is at work at the station. In such conditions the operation of "Violet" type products is impossible, so it was decided to install on the Soyuz ships a variant of the "ASU-VII" product called "ASU-VIID" (Figure 12). In this modification there is only one collector (instead of three) and therefore no slip indicator is used. The problem of corrosion resistance of the collector, which occurs in case of prolonged shutdown, is solved by sealing the collector during the shutdown period, which allows the system to be shut down for more than 180 days.[12]

IV. The toilets of the first orbital stations

For the first orbital stations, Skylab and Salut, toilets were designed for long and relatively comfortable crew stays in orbit, as the available volume of the habitation modules allowed. Some of the main goals of these designs were to increase urine and feces collection resources and to reduce manual operations through increased automation of use. Although the modernization of the design of the first station in comparison with the first manned spacecraft does not look like a cardinal solution, but rather a step in their development, it is a very important step of further improvement of space toilets on the way to regenerative life support complexes of Mir and ISS stations.

Skylab was the first U.S. long-duration station visited by 3 manned expeditions with 3-man crews in 1973-1974: May 25, 1973, 28 days 0 h 50 min, July 28, 1973 59 days 11 h 9 min, and November 16, 1973, 84 days 1 h 16 min. The Skylab toilet was the first U.S. toilet to use an air pump (fan) to suck urine through the urinal hose and feces into a holding tank. A filter installed at the inlet of the suction fan provided odor removal. The toilet was placed vertically on the wall of the Skylab cabin (Figure 13) in such a way that a male astronaut could use it conventionally "standing" for urine disposal. However, for feces disposal crew had to fix it to the wall parallel to the floor. While this is not an issue in microgravity, modern designers prefer to place the systems of daily use in weightlessness similar to use on Earth, to increase comfort and brain adaptation to microgravity conditions (except for sleeping cabins where a person is still closed off from the surrounding interior). Another fundamental and important innovation was the use of rigid containers with replaceable bags for feces and a toilet seat which was a removable neck of the excrement container. After use, the fecal bag was vacuumed to dry it and returned to the ground for analysis. The air/urine mixture was separated in a rotary separator and the liquid urine was transferred to a storage tank from which a sample could also be taken for return to Earth for analysis. In general, the Skylab toilet was a successful design solution with only two significant drawbacks: 1) to use the urinal, it was still necessary to dock it hermetically to the body with a rubber cuff, which is inconvenient and the toilet cannot be used by a female astronaut; 2) a large number of manual operations during use, especially to remove feces. The design of the Skylab toilet was an important milestone in the development of toilets and was partially used in the future.

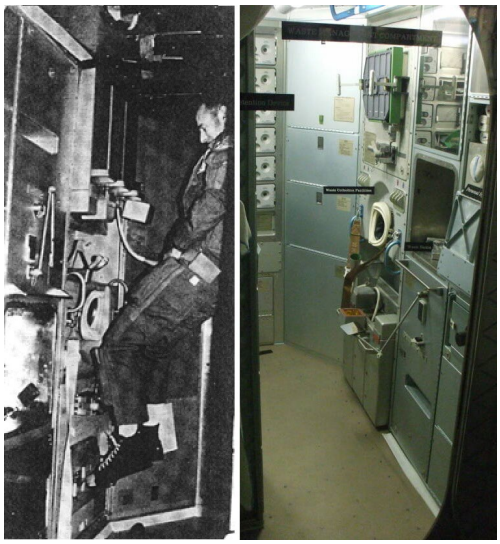


Figure 13. Skylab toilet

Salut was the Soviet program of long-term Inhabited Stations from 1971-1991. "Salut" was formed from the originally military program "Almaz", implemented in manned version only partially: Salut-3 (2 man.x13 days) manned flight and Salut-5 (2 man x64 days). The remaining manned flights took place on the first-generation stations with one docking unit: Salut-1 (3 people x22 days) and Salut-4 (2 people x92 days), and the second-generation stations with two docking units: Salut-6 (2-5 people x683 days) and Salut-7 (2-5 people x816 days). During 10 years of flights

of Salut-type orbital stations with increasing duration of continuous manned flights and increased quantity of crew members, the life support systems have also undergone a significant development. On the second-generation stations, a system of water regeneration from atmospheric moisture condensate (but not from urine) appeared, while the toilets were only improved on the basis of the toilet of the Soyuz spacecraft, having not changed fundamentally.

Special modifications of the ASU-VII system, called ASU-VIIE and ASU-VIIE-II, were used in the life-support systems of the Salyut space stations. The proven scheme with a moisture collector-separator was implemented but depending on specific tasks to ensure the system resources, variants of schemes were made with the use of unified elements easily replaceable in the process of operation: filters, collectors of increased capacity. In order to increase the reliability of the system after the slip indicator, an additional collector was introduced, designed to collect the liquid that "slipped" through the main collector in case of overflow. The operating resources of individual units (receivers, slip indicators, etc.) were limited by the operating time of an expedition.

Throughout the period of operation of the Salyut stations, work was carried out to improve the operational characteristics and reduce the load flow of the replaceable ASU elements. Based on a twenty-liter water tank (EDV) a design of a reusable collector called "EDV-SH" was created. In this collector, the diced porous foamed polyvinyl formal (TPVF) was placed in an elastic container inside a rigid body. After saturation of the collector foam with liquid waste, compressed air was supplied in the space between the rigid body and the elastic container, (from a hand pump or from a micro compressor), which uniformly squeezed the elastic container and extruded the liquid from the foam. The extruded liquid was directed through a hose to a container released from the drinking water. To control the flow of liquid, an EDV-SH shut-off and distribution valves were designed and installed on the inlet and outlet connections. The EDV-SH collector was tested under real flight conditions as part of the ASU- VIIE-II system at the Salyut-7 station, and as a standard device it was used as part of the ASU-8A product at the MIR station, where it was named Wring Collector SOT (Figure 14).

Figure 14. Wring collector SOT
1 - Metal casing; 2 - Soft bladder with liquid-retentive material TPVF;
3 - Air and urine inlet; 4 - Air outlet;
5 - Pressure delivery fitting

The toilets of the Salut stations kept all the positive features of the toilets of the Soyuz ships - they were quite comfortable for use with the same urine and feces receptacles and had more space for their use in the stations. However, they had no fundamental improvements, and to ensure long expeditions they required delivery and removal of a large number of consumable elements (urine collectors, feces liners, as well as air filters, which had a resource of a few months without urine pretreatment).[5-9,12]

V. Space Shuttle toilet

The development of the new generation of reusable spacecraft, the Space Shuttles, was accompanied by many fundamentally new technical solutions that gave a huge boost to the development of almost all systems. This was also true for space toilets. The toilets developed in the USA for the Space Shuttle program and in the USSR for the Buran program (although Buran never flew with a crew) differed significantly from their predecessors, had many improvements that formed the basis for subsequent developments, and could be called full-fledged space toilets.

The Space Shuttle program, which began development in 1972, flew 135 manned flights from 1981 to 2011 for a total of 1,323 days. The duration per flight ranged from 2 to 16.5 days and the number of crew members from 2 to 7. Many shuttle flights did involve docking with the Soviet space station MIR (June 1995-June 1998) and the ISS (Dec 2000 – July 2011), where the astronauts could use the life support of the local systems. However, during Shuttle orbital flights the large number of crew members required a normal, comfortable toilet and disposal of accumulated waste.

The toilet used on the Space Shuttle was called the Waste Collection System (WCS) (Figure 15) and included an anatomically comfortable toilet seat, leg and hip restraints, and a urinal hose with replaceable funnels (Figure 16). The collection of urine and feces in microgravity was provided by a transport airflow created by a fan combined with a centrifugal separator (fan separator). The separator removed air from the urine, which was discharged to the liquid waste tank through pitot tubes installed in the rotating liquid ring in the separator. From the liquid waste tank, the urine was periodically discharged overboard along with the condensate from the air conditioning system.

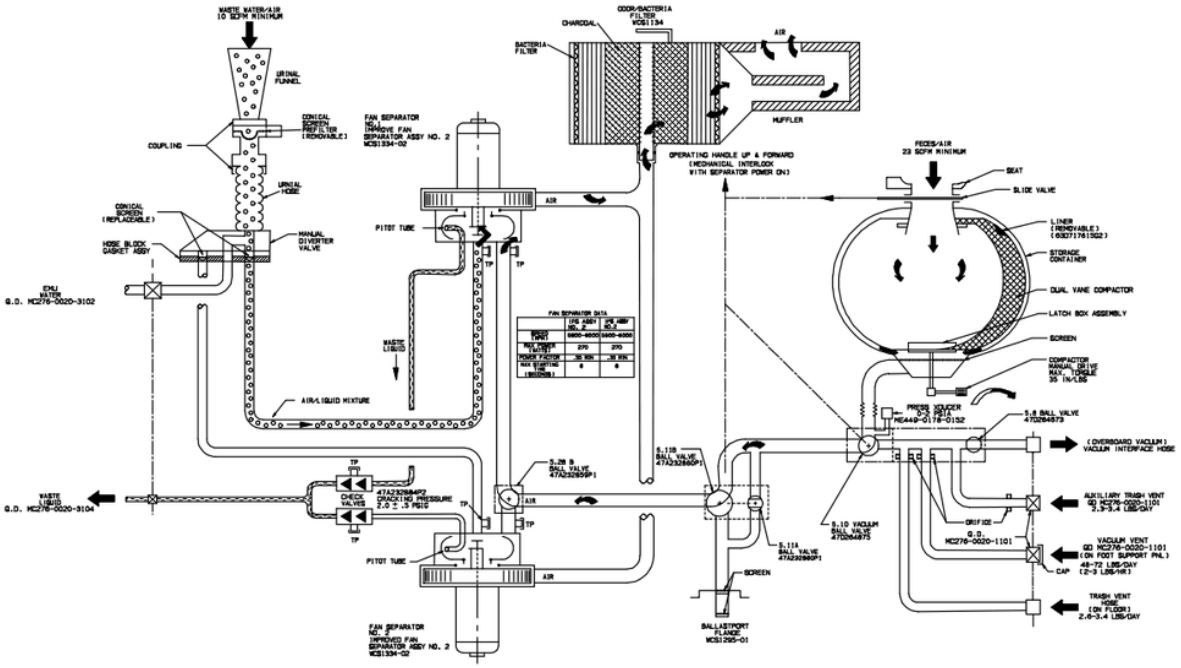


Figure 15. Space Shuttle WCS

Two separator fans were installed in parallel in the WCS, connected to the urine pump line by check valves, which could be used alternately, greatly increasing the reliability of the system. The fecal matter was conveyed by the transport air stream from the separator fan to a a container under the seat. Vanes in the container gathered material to one side and it was then exposed to an external vacuum to remove moisture, which dramatically slowed the decomposition process. The compacted and dehydrated feces were returned to Earth with the shuttle for disposal. The system proved to be convenient and fairly automated, though not without manual operations. The Shuttle WCS design was modified several times over the life of the program to correct issues with separator flooding, fecal collection/drying, and urine solids precipitation. The larger seat did require specific training in order to align with the fecal container. Later Shuttle missions incorporated Oxone tablets to pretreat urine and prevent formation of mineral precipitates.

Figure 16. Space Shuttle toilet

When the seven-day Shuttle baseline mission was extended to durations of 16-30 days, an Extended Duration Orbiter (EDO) WCS was developed. The EDO WCS design incorporated a larger commode seat, a fecal canister which can be changed out in-flight, an improved fecal compactor, and improvements to the urine liquid/gas separator.

The Shuttle WCS was designed for overboard discharge of urine, however this could not be done during Shuttle – ISS docked operations. The orientation of the Shuttle overboard vent was such that the urine could have contaminated the docking units and solar panels of the ISS station when the Shuttle it was docked. Therefore, Joint Operations rules prohibited dumping the Shuttle's liquid waste tank near the station. Due to the limited volume of the waste tanks, this lead to the need to redistribute the liquids in flight with the transfer of water and condensate to the station for processing.[12]

The ASU-8 toilet was developed for the Buran spacecraft. In it, while maintaining the basic design solutions, there were significant changes in the elemental composition in comparison with the "ASU- VII" type systems of Soyuz and Salut. Thus, the tank with replaceable disposable liners was replaced by a tank with a removable container for solid waste (with a resource of at least 30 crew-days) and with lighter packaging in the liners. In other words, the Soviet toilet finally got a toilet seat with a urinal (Figure 17). The overflow indicator, which required a visual check to determine when the collector-separator was full, was replaced by an overflow alarm, which gives an electrical signal

Figure 17. ASU-8 toilet

with a display on the control panel when the collector overflows. In order to create more comfortable conditions for use, the ASU-8 has a more powerful fan, which creates a higher flow rate of transporting air. A volume of TPVF treated with a preservative was used in the collectors, which reduces the load on the deodorizing filter by lowering the ammonia concentration in the system.

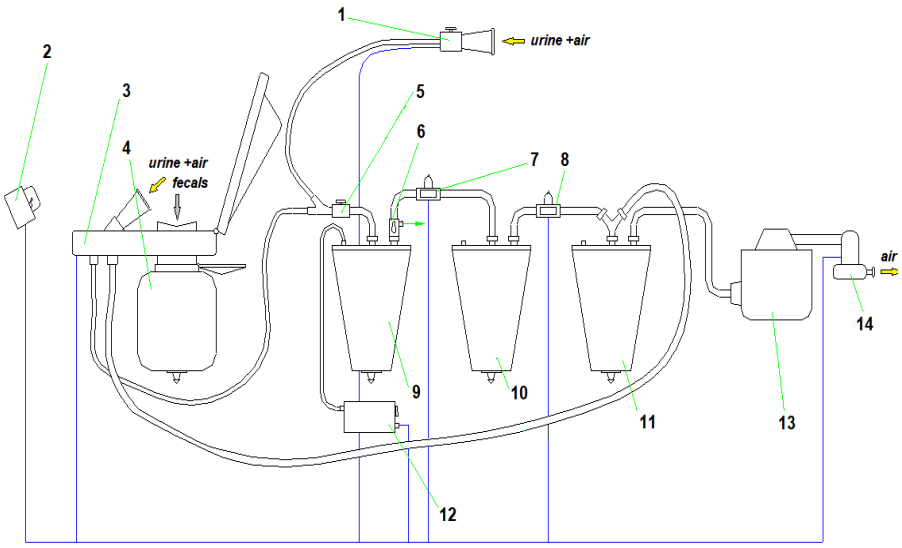
Depending on the variants of flight duration and crew composition, system configuration variations were considered, which differed in the number of replaceable elements (collectors, filters, etc.). This toilet, with some modifications based on the experience gained during the operation of the Salut stations, was installed at the Mir station and was used there in the initial period before the first system of water regeneration from urine was flown.

VI. Toilets of the Mir orbital station

The Soviet orbital station Mir was the first truly multi-module long-duration orbital station and was in orbit from 1986 to 2001. Manned flights to the station began with a unique flight from the decommissioned Salyut-7 station and back in March-June 1986, and then continuous manned operation of the station continued from February 6, 1987 to August 28, 1999. Crews rotated from six months to a year or more (the record of 437 days 17 hours 58 minutes was set by Dr. Valery Polyakov). Permanent and visiting crews were transported to the Mir station by Soyuz-TM spacecraft and the Space Shuttle, which flew regularly to the station, making 9 flights from June 1995 to June 1998 (7 - Atlantis, 1 - Endeavor and 1 - Discovery). The Mir Station spent 5511 days in Earth orbit, 4594 of which were inhabited, making 86,331 orbits around the planet. Mir ceased to exist on March 23, 2001, after a controlled orbital descent.

The first semi-enclosed regenerative life support complex was installed on the Mir station, including water regeneration from urine since 1990. The development of the regenerative life support complex also determined the design of the toilet used.

Until 1990, Mir station used the ASU-8A toilet, based on the ASU-8 for Buran (Figure18).



1 -Urine receptacle.
2 - Control panel.
3 – Receptacle.
4 - Solid waste container (KTO).
5 - Shutoff manual valve (K1).
6 - Distributing manual valve (K2).
7,8 - Liquid droplet carryover indicators.
9 - Main Wring collector (SOT1).
10 - Additional Wring collector (SOT2).
11- Backup Wring collector (SOT3).
12 – Compressor.
13 - Air filter.
14 – Fan.

Figure 18. ASU-8A on MIR station

A transport air flow created by the fan (14), which is switched on manually by means of the toggle switch on the control panel (2) or automatically by opening the valve of the urine receptacle (1) or the lid of the seat (labeled 3 receptacles in Figure 18). The air released into the cabin atmosphere is purified in the deodorizing air filter (13). The ASU-VII emergency urine receptacle with wringer is provided as an emergency means in case the fan for urine collection cannot be switched on.

Fecal matter is removed in disposable bag liners that are attached above the inlet neck of the interchangeable solid waste container (KTO) (4). After use, the liner is emptied for storage in the KTO, which is designed to hold thirty used liners. After filling, the KTO is sealed with a hermetic lid and stored until the KTO and other trash is removed from the station by the Progress cargo vehicle. Urine is retained in the main wring collector - a static separator of the gas-liquid mixture (9). When the porous material becomes saturated with liquid waste, the liquid droplet carry-over indicators (7) are triggered, and a light signal appears on the control panel indicating the need to empty the working wring collector. For this purpose, compressed air is supplied from the compressor (12) to the moisture collector, forcing the liquid waste to be transferred to empty tanks which were previously used to bring potable water. In addition to urine, the ASU-8A received water from the washroom. When the additional collector (10) overfills, a liquid droplet carryover indicator (8) is triggered, providing information to telemetry, and the wring collectors are replaced.

Work on improving the system elements continued even after the station was put into operation. For example, a more reliable scheme of the liquid carryover indicator was developed, and the system was equipped with a backup wring collector (11). The air filter was changed after the appearance of odors during the system operation, and the KTO was changed as soon as it was filled.

The main advantages of the ASU-8A over the systems used on the "Salut" include:

- Reduction of manual operations in the process of isolation of solid waste from the cabin atmosphere and weight of consumables per use (by using solid waste containers with disposable liners),
- Increased air flow (by using a larger fan), which improves the hygienic conditions for using the system,
- Simplified use of the system due to the use of the liquid indicator instead of the slip indicator used in "Salut",
-Increased safety of the system due to the application of the liquid indicator after the reserve collector and the use of a third collector.

The undoubted disadvantages of the system include the need for periodic (once every 3-5 days) operations to empty the moisture collector, which could lead to leaks of urine into the atmosphere if the crew made mistakes.

Introduction of physical-chemical water regeneration systems from urine into the life support complex of orbital stations was required as part of the modernization of space toilets. It was made possible with the addition of the chemical preservation of urine to ensure chemical and biological stability to prevent its decomposition during thermal or vacuum-thermal water extraction. The first long-functioning system for regeneration of water from urine was the SRV-U system on MIR station, delivered into orbit as part of module "Kvant-2" in November of 1989. It was connected in a single functional scheme with a sewage-sanitary device with the means for receiving and pretreatment of urine, designated ASU SPK-U. The ASU-SPK-U used the same components as in ASU-8A: receptacle and urine receptacle, fan, air filter, and connecting elements. The separate ASU-8A was no longer in operation and was eventually removed from the station.

In ASU SPK-U the method of urine pretreat was by adding an aqueous solution of sulfuric acid with the addition of chromium oxide (H2SO4 + H2O + CrO3). In addition, the main innovation of the system was the use of a centrifugal separator pump to automatically separate liquid urine from transport air and feed it into a regeneration system or a tank for temporary storage.

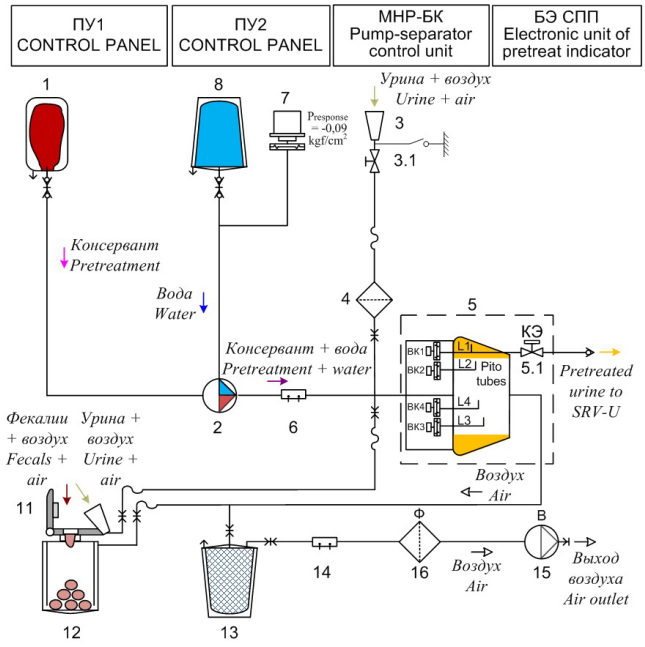


Figure 19. ASU SPK-U of Mir station

1 Pretreat tank. 2. Pretreat and flush water doze-pump. 3. Urine receptacle. 3.1 Urine receptacle valve. 4. Insert filter. 5. Pump-separator. 5.1 Solenoid valve. 6. Pretreat quality sensor.7. Flush water tank sensor unit 8. Flush water tank (EDV). 11. 11. Receptacle 12. Solid waste container (SWC). 13. Wring collector SOT 14. Liquid droplet carryover indicator. 15. Fan. 16. Air filter.

ASU SPK-U (Figure19) has 2 urinal receptacles, one mounted on the receptacle seat (11) and the other on a separate hose (3). The unit is actuated by switches when the urine receptacle (3) is removed from the retainer or when the receptacle lid (11) is opened. This action triggers a signal which actuates the rotary pump-separator (5), and when it reaches operational mode the fan (15) is actuated, which provides the flow of transport air. Urine from the crew is sucked into the urine receptacle (3) with an air stream by the fan (15). Acid pretreatment chemicals from the pretreatment tank (1), providing chemical and microbiological stability of urine, and flush water (8) are metered out by the dose-pump (2) into the urine-airflow. The urine is separated from the transport air in the rotary pump-separator (5). The transport air passes through the wring collector-backup static separator (13) filled with a liquid-retentive material, is cleared from impurities via sorption in the filter (16) and vented to the atmosphere. The urine with pretreatment chemicals and flush water leaves the separator via Pitot-tube and is fed to the urine collection tank for storage or for water reclamation. The urine with pretreatment chemicals can be stored without chemical and bacterial decomposition for more than one year. Pretreat quality is controlled via pretreat quality sensor (6) by electric conductivity of pretreat with flush water mixture. Emptying of the flush water tank is monitored by a membrane vacuum sensor (7), filling of the urine collection tank is monitored by a membrane overpressure sensor.

The design and control algorithm ensured stability of the daily operation of the toilet for continuous operation with simultaneous regeneration of water from urine in the SRV-U system almost until the end of the Mir station operation. High efficiency of urine pre-treatment was confirmed by obtaining more than 6000 liters of water from urine in the SRV-U system and then used for oxygen generation by electrolysis. The SRV-U system had high power consumption and in case of power supply shortage, which periodically happened at Mir station, the ASU SPK-U was also used without urine recycling and in total provided reception and utilization of 11100 liters of urine.[5,6,11] ASU SPK-U turned out to be a convenient and reliable system, which was operated at Mir station from 1990 to the end in 2001, and modified versions of the ASU SPK-U were further used as Russian-made ISS toilets.[12]

VII. ISS toilets

The International Space Station is the world's largest crewed space project to date, having been in low Earth orbit since November 20, 1998, and continuously crewed since Nov 2, 2000. The ISS represents an international collaboration with the participation of 14 countries and visited during more than 60 expeditions by over 260 astronauts from 21 countries. The permanent crew increased with the construction of the station in orbit from 2 to 7 people with a short-term increase to 11 people during expedition visits. Four types of spacecrafts from two countries have been used to transport the crew to the ISS: Soyuz-TM and -TMA (Russia), Space Shuttle (USA), Crew Dragon (USA), Starliner (USA). The ISS Life Support Systems (LSS), designed to ensure a long stay of a large number of people, was designed to support a regenerative subsystem. It has been developed throughout the construction and operation of the ISS with the addition and modernization of systems. For example, all ISS toilets were initially designed with urine pre-treatment to enable processing in the urine processor.

As of 2025, there are three Russian-designed toilets on the ISS - two in RS and one in USOS, and one American-designed Universal Waste Management System (UWMS). Figure20 shows the schematic diagrams of the Russian-designed ASU with differences for different variants.

The first ASU-SPK-UM toilet, based on the ASU-SPK-U, was installed on the Service Module of the Russian segment of the ISS and was the only toilet on the ISS from November 2000 to December 2008. Its main difference from the ASU-SPK-U was that it was designed for autonomous operation without connection to the urine processor, as the first urine processor would not arrive on the US Segment until December 2008 and on the Russian Segment in April 2018.Urine was delivered to the portable EDV tanks, which were then manually transferred and docked to disposal tanks, or to the US Urine Processor Assembly (UPA) or the Russian urine processor designated SRV-U-RS for water regeneration. The ASU-SPK-UM included a set of ASU-8AM elements based on the modernization of the ASU-8A. The ASU-8AM set differed from the ASU-8A in the design of the receiver (Figure 20 item 11), which was intended only for feces and did not have a urine receptacle; as well as absence of a switch that started the system when the lid was opened. It started when the valve of the urine receptacle (3.1) was opened (the switch on the valve was introduced during operation at the Mir station). The solid waste container (12) is also different, it has a collapsible conical design versus the non-collapsible cylindrical КТО of Mir station that allows for compact nesting of multiple units, which saves space when delivering and storing the necessary large quantity: the container bodies and bottoms are stacked in separate compact stacks. At the same time, its volume is smaller, containing only 20 person-days instead of 30. Also, in the ASU-SPK-UM, the filter (16) and the fan (15) have been rearranged, the filter is now at the outlet of the system, and a modernized electronic unit of the pretreat quality sensor has been utilized. The other units are practically the same, as is the operating principle.

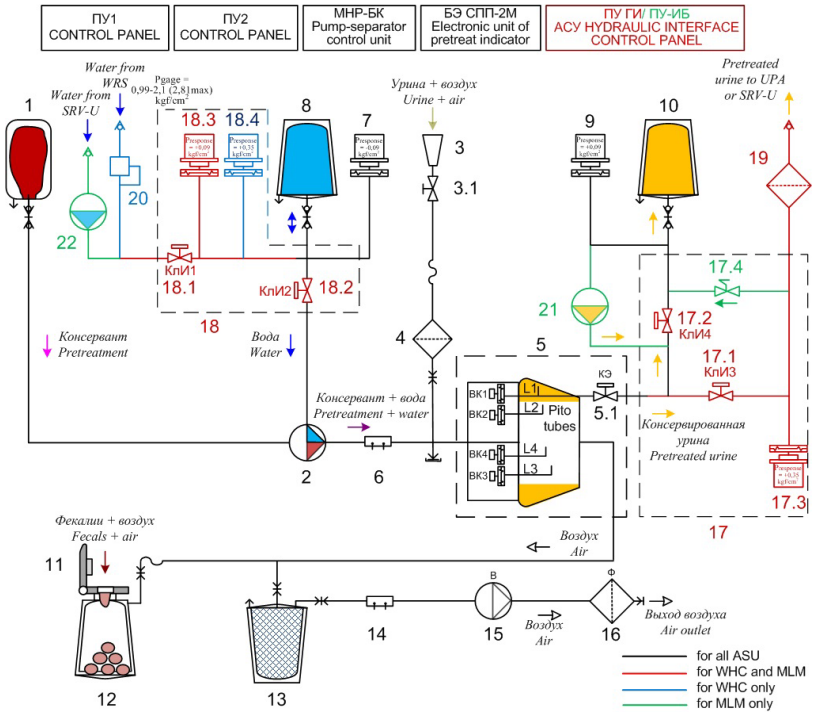


Figure 20. ASU ISS diagram

1 Pretreat tank. 2. Pretreat and flush water dose-pump. 3. Urine receptacle. 3.1 Urine receptacle valve. 4. Insert filter. 5. Pump-separator. 5.1 Solenoid valve. 6. Pretreat quality sensor.7. Flush water tank sensor unit 8. Flush water tank (EDV). 11. 11. Receptacle 12. Solid waste container (KTO).13. Wring collector SOT 14. Liquid droplet carryover indicator. 15. 15. Fan. 16. Air filter. 17. Urine interface valve unit. 17.1,17.2 Urine valve. 17.3. Urine interface sensor unit. 17.4 Check valve. 18. Water interface units. 18.1,18.2 Water valve. 18.3. Water interface sensor unit. 19. Urine filter. 20. Pressure regulator. 21. Water pump. 22. Urine transfer pump

The second toilet appeared on the ISS in December 2008 as part of the Waste and Hygiene Compartment (WHC) in the US Segment and according to the Russian classification it is called ASU-SPK-UM-IB. In 2006-2008 a unique international WHC/ASU & Cabin project was carried out with the participation of American and Russian specialists, allowing for joint work on engineering design, support of operations planning as well as on orbit mission support and resupply and pre-flight preparation of replacement equipment. This collaborative project continues today with improvements to design and operations as appropriate for a long-term mission. In order to connect the US water supply system and the UPA, the water and urine interface valve units (17,18), and hydraulic interface control panels were introduced, and cable network was updated. This made it possible to automate the filling of the flush water tank (8) and the supply of urine to the UPA or to the portable tank EDV (10). The ASU-SPK-UM-IB/WHC uses a chemical solution based on orthophosphoric acid for urine pre-treatment, which can also be used in the ASU-SPK-UM. The switch to an alternative preservative based on orthophosphoric acid was mandated by NASA in 2013-2014 to prevent UPA failure due to gypsum formation in urine brines when sulfuric acid combines with calcium leached from human bones in microgravity. The other components and the principles of operation are the same.[9,12]

The third Russian toilet ASU-SPK-UM MLM arrived on the ISS in July 2021 as part of the sanitary and hygienic support facilities (SSHO) of the Nauka Multipurpose Laboratory Module (MLM), together with the new urine processor SRV-UM. ASU MLM can be used both autonomously with urine collection in the EDV, and in automatic mode together with SRV-UM according to the connection scheme. This combines the features of ASU SPK-U Mir and ASU SPK-UM-IB/WHC, adding the interface valve units for water (18) and urine, the hydraulic interface control panel in the SSHO, as well as water (21) and urine (22) transfer pumps. The basic units and operation are the same as the ASU-SPK-UM.

The fourth ISS toilet, the new US-designed Universal Waste Management System (UWMS) (Figure 21), arrived at USOS in October 2020 (individual parts had been delivered since

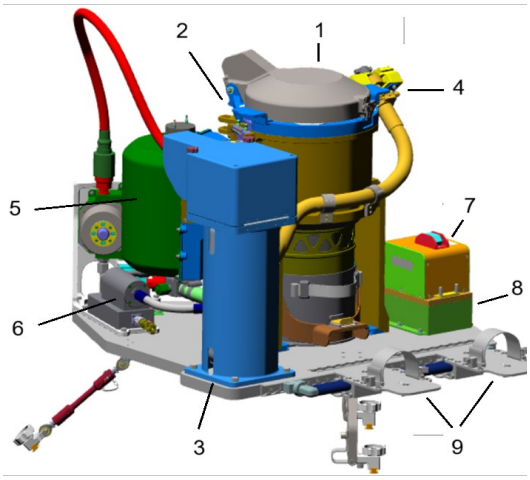


Figure 21. UWMS

1 Lid. 2. Seat. 3. Pretreat tank. 4. Urine hose. 5. Dual Fan Separator. 6. Dose Pump. 7. Power box 8. Data recorder. 9. Foot restraint

February 2019). The "universal" in UWMS is key: the central design concept can be easily integrated into various spacecraft and life support systems. The main purpose of the installation on the ISS is flight testing to verify usability and reliability. The toilet was designed to address astronaut feedback on comfort and ease of use. It is also 65% smaller and 40% lighter than the current ISS toilet, the ASU-SPK-UM. The funnel and seat can be used simultaneously, reflecting feedback from female astronauts. The UWMS seat has been designed to be much smaller and a conformal shape that appears pointy, but it's ideal in microgravity. It provides ideal body contact to make sure everything goes where it should. In the UWMS, as in the Space Shuttle EDO WCS, the fan that provides the airflow to transport the urine is combined with a centrifugal separator to remove the air and direct the urine to the UPA for processing or to a removable tank. Urine pre-treatment is performed by adding a chemical preservative based on orthophosphoric acid for the ISS version, and a Russian-designed pre-treatment tank is used. The bellows pretreat and flush water dose pump is fundamentally different from the piston pump in ASU-SPK-UM, but the basic function and quantities delivered are very similar. A new pretreatment quality control sensor is also being used. Fecal matter is collected in replaceable containers, also of new design, where it is compressed to save space. UWMS has had several hardware issues during its initial ISS installation and checkout period, which have been documented in numerous other ICES papers.[13-19]

VIII. New space toilets

Toilet development continues with the continuation of manned missions, including upgrades to existing toilets and development of new ship and station toilets.

On the RS ISS, the ASU-SPK-UM is being upgraded with a new separator pump, control panel, waterless preservative dispenser, new preservative control sensor, new pretreatment tank and the introduction of a sensor for monitoring of its emptying. The name of the upgraded toilet is ASU-SPK-UM2, and the transition to it on the Service module of RS ISS is made by phased replacement of elements, with continue using of the ASU-SPK-UM.

Among the spacecraft's projects, the ASU-SPK-UM1 project for the Russian spacecraft Orel is fundamentally new. This toilet uses a completely new static separator with hydrophilic polymer membranes and moisture-absorbing filler impregnated with preservative. This chemical pre-treatment aqueous solution has a pH of 3.5, which is slightly higher than the sulphuric or orthophosphoric acid-based pH 1.5-2.0 for ASU SPK-UM, WHC or UWMS, but it prevents the moisture absorbing material from decomposing and at the same time ensures that the urine is pre-treated for storage or water recovery. The liquid urine is pumped out by a membrane pump that creates a constant pressure drop across the membranes, and then the urine is pumped into the ship's tanks. One vehicle tank is initially empty and designed for urine, and the other tank is filled with urine after the drinking water is used up. In the ASU SPK-UM1, urine and feces are collected with the help of transport air flow created by a fan and a container (seat), solid waste container, urine container, fan and air filter from the ASU-8AM with some modifications. For the restroom in spacecraft, there is a compartment that is visually closed from the crew seats and provides some privacy. This is a good example of using the experience of successful station and vehicle toilets, with reduced weight and size, but with urine pre-treatment allowing also water to be reclaimed from it during flights to new orbital stations.

The Crew Dragon has a new toilet with a static separator and two redundant fans. The volume for urine storage is limited by the short program of autonomous flight up to 1 day. This toilet also uses the previous spacecrafts experience but is made in a minimal functional version. The disadvantages of this toilet include its unfortunate location on the docking station right in front of the seats, which does not provide privacy.

The initial UWMS design was developed for the NASA Orion Artemis-2 mission with a flight test on the ISS. The Orion unit was delivered in 2019 and installed in the Artemis-2 Vehicle. For lunar/planetary missions, US teams have been developing the Lunar On-Orbit (LOO). The LOO is designed to operate in both microgravity and partial gravity and was described in ICES-2023-43.[15] Future commercial spacecraft, space stations and even planetary missions are also looking at the space toilet lessons learned and developing innovative solutions for a complicated problem of collecting and disposing of human waste in space.

IX. Conclusion

Space toilets have evolved over many years, improving in design, ease of use, reliability, and functionality - from inconvenient disposable hygienic devices on the first spacecraft, to transport airflow systems with urine separation on later spacecraft and the first orbital stations, to full-fledged comfortable toilets with urine pre-treatment for subsequent water regeneration as part of a closed-loop life-support regeneration complex.

The U.S. and Soviet/Russian developments proceeded along parallel paths, eventually arriving at similar solutions with different design variations.

The success of new toilet designs should and does come from using the historical experience of previous designs, taking into account the tasks of crewed missions, and making the necessary improvements in reliability, comfort of use, and the possibility of incorporation into future life support complexes.

Acknowledgments

The authors would like to acknowledge the many US and Russian engineers and scientists that have contributed to the processes development, design and operation of the toilet systems, and especially the toilet developers Leonid Bobe from NIIchimmash, Alexander Belov retired from NPP Zvezda, Richard L. Sauer retired from NASA.

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